

Material Hardness

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1. WHAT IS HARDNESS?

The Metals Handbook defines hardness as "Resistance of metal to plastic deformation, usually by indentation. However, the term may also refer to stiffness or temper, or to resistance to scratching, abrasion, or cutting. It is the property of a metal, which gives it the ability to resist being permanently, deformed (bent, broken, or have its shape changed), when a load is applied. The greater the hardness of the metal, the greater resistance it has to deformation.

In mineralogy the property of matter commonly described as the resistance of a substance to being scratched by another substance. In metallurgy hardness is defined as the ability of a material to resist plastic deformation.

The dictionary of Metallurgy defines the indentation hardness as the resistance of a material to indentation. This is the usual type of hardness test, in which a pointed or rounded indenter is pressed into a surface under a substantially static load.

2. HARDNESS MEASUREMENT

Hardness measurement can be defined as macro-, micro- or nano- scale according to the forces applied and displacements obtained [1].

Measurement of the macro-hardness of materials is a quick and simple method of obtaining mechanical property data for the bulk material from a small sample. It is also widely used for the quality control of surface treatments processes. However, when concerned with coatings and surface properties of importance to friction and wear processes for instance, the macro-indentation depth would be too large relative to the surface-scale features.

Where materials have a fine microstructure, are multi-phase, non-homogeneous or prone to cracking, macro-hardness measurements will be highly variable and will not identify individual surface features. It is here that micro-hardness measurements are appropriate.

Microhardness is the hardness of a material as determined by forcing an indenter such as a Vickers or Knoop indenter into the surface of the material under 15 to 1000 gf load; usually, the indentations are so small that they must be measured with a microscope. Capable of determining hardness of different microconstituents within a structure, or measuring steep hardness gradients such as those encountered in casehardening. Conversions from microhardness values to tensile strength and other hardness scales (e.g. Rockwell) are available for many metals and alloys[2].

Micro-indenters works by pressing a tip into a sample and continuously measuring: applied load, penetration depth and cycle time.

Nano-indentation[3] tests measure hardness by indenting using very small, on the order of 1 nano-Newton, indentation forces and measuring the depth of the indentation that was made. These tests are based on new technology that allows precise measurement and control of the indenting forces and precise measurement of the indentation depths. By measuring the depth of the indentation, progressive levels of forcing are measurable on the same piece. This allows the tester to determine the maximum indentation load that is possible before the hardness is compromised and the film is no longer within the testing ranges. This also allows a check to be completed to determine if the hardness remains constant even after an indentation has been made.

There are various mechanisms and methods that have been designed to complete nano-indentation hardness tests. One method of force application is using a coil and magnet assembly on a loading column to drive the indenter downward. This method uses a capacitance displacement gauge. Such gages detect displacements of 0.2 to 0.3 NM (nanometer) at the time of force application. The loading column is suspended by springs, which damps external motion and allows the load to be released slightly to recover the elastic portion of deformation before measuring the indentation depth. This type of nano-indentation machine can be seen in Figure 1.

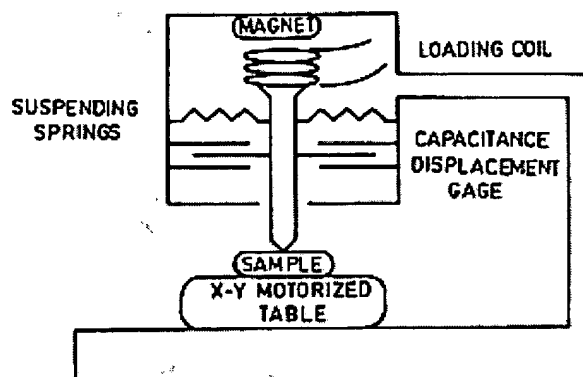


Figure 1

Another method of nano-indentation uses a long-range piezo driver and an elastic element as shown in Figure 2. When the indenter is moved downward by the piezo driver, the elastic element resists the movement and establishes a force. This force is measurable by knowing the distance that the indenter moved downward after touching the film surface. An LVDT (linear variable differential transform) records the position of the shaft, thereby measuring the indentation depth and the spring force applied at one time.

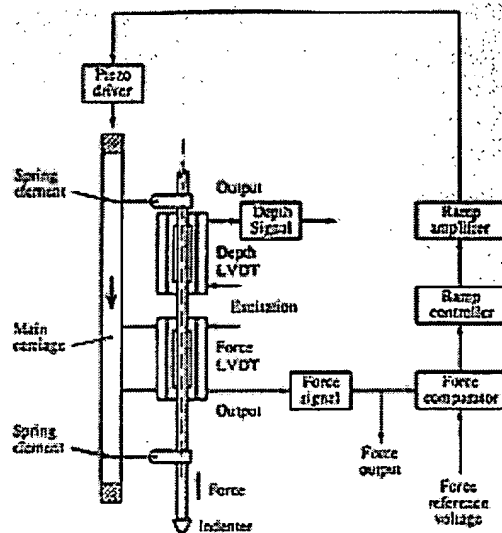


Figure 2

3. HARDNESS MEASUREMENT METHODS

There are three types of tests used with accuracy by the metals industry; they are the Brinell hardness test, the Rockwell hardness test, and the Vickers hardness test. Since the definitions of metallurgic ultimate strength and hardness are rather similar, it can generally be assumed that a strong metal is also a hard metal. The way the three of these hardness tests measure a metal's hardness is to determine the metal's resistance to the penetration of a non-deformable ball or cone. The tests determine the depth which such a ball or cone will sink into the metal, under a given load, within a specific period of time. The followings are the most common hardness test methods used in today's technology:

1. Rockwell hardness test
2. Brinell hardness
3. Vickers
4. Knoop hardness
5. Shore

3.1. Rockwell Hardness Test

The Rockwell Hardness test is a hardness measurement based on the net increase in depth of impression as a load is applied. Hardness numbers have no units and are commonly given in the R, L, M, E and K scales. The higher the number in each of the scales means the harder the material.

Hardness has been variously defined as resistance to local penetration, scratching, machining, wear or abrasion, and yielding. The multiplicity of definitions, and corresponding multiplicity of hardness measuring instruments, together with the lack of a fundamental definition, indicates that hardness may not be a fundamental property of a material, but rather a composite one including yield strength, work hardening, true tensile strength, modulus of elasticity, and others. In the Rockwell method of hardness testing, the depth of penetration of an indenter under certain arbitrary test conditions is determined. The indenter may either be a steel ball of some specified diameter or a spherical diamond-tipped cone of 120° angle and 0.2 mm tip radius, called Brale. The type of indenter and the test load determine the hardness scale(A, B, C, etc)[4].

A minor load of 10 kg is first applied, which causes an initial penetration and holds the indenter in place. Then, the dial is set to zero and the major load is applied. Upon removal of the major load, the depth reading is taken while the minor load is still on. The hardness number may then be read directly from the scale.

The hardness of ceramic substrates can be determined by the Rockwell hardness test, according to the specifications of ASTM E-18. This test measures the difference in depth caused by two different forces, using a dial gauge. Using standard hardness conversion tables, the Rockwell hardness value is determined for the load applied, the diameter of the indenter, and the indentation depth.

The hardness testing of plastics is most commonly measured by the Rockwell hardness test or Shore (Durometer) hardness test. Both methods measure the resistance of the plastic toward indentation. Both scales provide an empirical hardness value that doesn't correlate to other properties or fundamental characteristics. Rockwell hardness is generally chosen for 'harder' plastics such as nylon, polycarbonate, polystyrene, and acetal where the resiliency or creep of the polymer is less likely to affect the results.

The results obtained from this test are a useful measure of relative resistance to indentation of various grades of plastics. However, the Rockwell hardness test does not serve well as a predictor of other properties such as strength or resistance to scratches, abrasion, or wear, and should not be used alone for product design specifications.

The Rockwell hardness tester to measure the hardness of metal measures resistance to penetration like the Brinell test, but in the Rockwell case, the depth of the impression is measured rather than the diametric area. With the Rockwell tester, the hardness is indicated directly on the scale attached to the machine. This dial like scale is really a depth gauge, graduated in special units. The Rockwell hardness test is the most used and versatile of the hardness tests.

For soft materials such as copper alloys, soft steel, and aluminum alloys a 1/16" diameter steel ball is used with a 100-kilogram load and the hardness is read on the "B" scale. In testing harder materials, hard cast iron and many steel alloys, a 120 degrees diamond cone is used with up to a 150 kilogram load and the hardness is read on the "C" scale. The Rockwell test uses two loads, one applied directly after the other. The first load, known as the "minor", load of 10 kilograms is applied to the specimen to help seat the indenter and remove the effects, in the test, of any surface irregularities. In essence, the minor load creates a uniformly shaped surface for the major load to be applied to. The difference in the depth of the indentation between the minor and major loads provides the Rockwell hardness number. There are several Rockwell scales other than the "B" & "C" scales, (which are called the common scales). The other scales also use a letter for the scale symbol prefix, and many use a different sized steel ball indenter. A properly used Rockwell designation will have the hardness number followed by "HR" (Hardness Rockwell), which will be followed by another letter which indicates the specific Rockwell scale. An example is 60 HRB, which indicates that the specimen has a hardness reading of 60 on the B scale. There is a second Rockwell tester referred to as the "Rockwell Superficial Hardness Tester". This machine works the same as the standard Rockwell tester, but is used to test thin strip, or lightly carburized surfaces, small parts or parts that might collapse under the conditions of the regular test. The Superficial tester uses a reduced minor load, just 3 kilograms, and has the major load reduced to either 15 or 45 kilograms depending on the indenter, which are the same ones used for the common scales. Using the 1/16" diameter, steel ball indenter, a "T" is added (meaning thin sheet testing) to the superficial hardness designation. An example of a superficial Rockwell hardness is 15T-22, which indicates the superficial hardness as 22, with a load of 15 kilograms using the steel ball. If the 120; diamond cone were used instead, the "T" would be replaced with "N".

instead, the "T" would be replaced with "N". The ASTM (American Society for Testing & Materials)

has standardized a set of scales (ranges) for Rockwell hardness testing. Each scale is designated by a letter.

SCALE TYPICAL APPLICATIONS

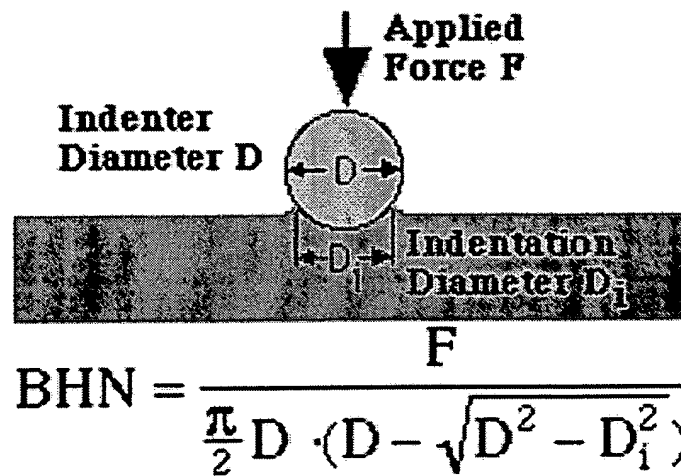
-
- A Cemented carbides, thin steel and shallow case hardened steel
 - B Copper alloys, soft steels, aluminum alloys, malleable iron, etc.
 - C Steel, hard cast irons, pearlitic malleable iron, titanium, deep case hardened steel and other materials harder than B 100
 - D Thin steel and medium case hardened steel and pearlitic malleable iron
 - E Cast iron, aluminum and magnesium alloys, bearing metals
 - F Annealed copper alloys, thin soft sheet metals
 - G Phosphor bronze, beryllium copper, malleable irons
 - H Aluminum, zinc, lead
 - K, L, M, P, R, S, V Bearing metals and other very soft or thin materials, including plastics.

3.2. Brinell Hardness Test

Brinell hardness is determined by forcing a hard steel or carbide sphere of a specified diameter under a specified load into the surface of a material and measuring the diameter of the indentation left after the test. The Brinell hardness number, or simply the Brinell number, is obtained by dividing the load used, in kilograms, by the actual surface area of the indentation, in square millimeters. The result is a pressure measurement, but the units are rarely stated [5].

The Brinell hardness test [6] uses a desk top machine to press a 10mm diameter, hardened steel ball into the surface of the test specimen. The machine applies a load of 500 kilograms for soft metals such as copper, brass and thin stock. A 1500 kilogram load is used for aluminum castings, and a 3000 kilogram load is used for materials such as iron and steel. The load is usually applied for 10 to 15 seconds. After the impression is made, a measurement of the diameter of the resulting round impression is taken. It is measured to plus or minus .05mm using a low-magnification portable microscope. The hardness is calculated by dividing the load by the area of the curved surface of the indentation, (the area of a hemispherical surface is arrived at by multiplying the square of the diameter by 3.14159 and then dividing by 2). To make it easier, a calibrated chart is provided, so with the diameter of the indentation the corresponding hardness number can be referenced. A well structured Brinell hardness number reveals the test conditions, and looks like this, "75 HB 10/500/30" which means that a Brinell Hardness of 75 was obtained using a 10mm diameter hardened steel with a 500 kilogram load applied for a period of 30 seconds. On tests of extremely hard metals a tungsten carbide ball is substituted for the steel ball. Among the three hardness tests discussed, the Brinell ball makes the deepest and widest indentation, so the test averages the hardness over a wider amount of material, which will more accurately account for multiple grain structures, and any irregularities in the uniformity of the alloy.

The Brinell hardness test was one of the most widely used hardness tests during World War II [7]. For measuring armour plate hardness the test is usually conducted by pressing a tungsten carbide sphere 10mm in diameter into the test surface for 10 seconds with a load of 3,000kg, then measuring the diameter of the resulting depression. The BHN is calculated according to the following formula:



where

BHN = the Brinell hardness number

F = the imposed load in kg

D = the diameter of the spherical indenter in mm

D_i = diameter of the resulting indenter impression in mm

Several BHN tests are usually carried out over an area of armour plate. On a typical plate each test would result in a slightly different number. This is due not only to minor variations in quality of the armour plate (even homogenous armour is not absolutely uniform) but also because the test relies on careful measurement of the diameter of the depression. Small errors in this measurement will lead to small variations in BHN values. As a result, BHN is usually quoted as a range of values (e.g. 210 to 245, or 210-245) rather than as a single value.

The BHN of face hardened armour uses a back slash \ to separate the value of the face hardened surface from the value of the rear face. For example, a BHN of 555\353-382 indicates the surface has a hardness of 555 and the rear face has a hardness of 353 to 382.

The Brinell Hardness Test described above is called HB 10/3000 WC and was the type of test used by the Germans in World War II. Other types of hardness tests use different materials for the sphere and/or different loads. Softer materials deform at high BHN which is why tungsten carbide (a very hard material) is used to measure armour plate. Even so, as the BHN goes above 650 the tungsten carbide ball begins to flatten out and the BHN values indicate a greater difference in hardness than there actually is, while above 739 the ball flattens out so badly that it cannot be used.

When there are widely different values for quoted BHN then the cause may be use of a Poldi Hardness Tester instead of the Brinell Hardness Test. The Poldi Hardness Tester is less accurate but could be used in the field. The Poldi Hardness Test has the advantage that the testing unit is portable, so measurements can be carried out in the field, e.g., on captured enemy vehicles after a battle. The Poldi portable unit relies on a hammer blow impression in a standardized sample. This test is much less accurate than the Brinell Hardness Test.

ASTM E-10 is a standard test for determining the Brinell hardness of metallic materials. The load applied in this test is usually 3,000, 1,500, or 500 kgf, so that the diameter of the indentation is in the range 2.5 to 6.0 mm. The load is applied steadily without a jerk. The full test load is applied for 10 to 15 seconds. Two diameters of impression at right angles are measured, and the mean diameter is used as a

basis for calculating the Brinell hardness number (BHN), which is done using the conversion table given in the standard [8].

3.3. Vickers Hardness Test

It is the standard method for measuring the hardness of metals, particularly those with extremely hard surfaces: the surface is subjected to a standard pressure for a standard length of time by means of a pyramid-shaped diamond. The diagonal of the resulting indentation is measured under a microscope and the Vickers Hardness value read from a conversion table [9].

Vickers hardness is a measure of the hardness of a material, calculated from the size of an impression produced under load by a pyramid-shaped diamond indenter. Devised in the 1920s by engineers at Vickers, Ltd., in the United Kingdom, the diamond pyramid hardness test, as it also became known, permitted the establishment of a continuous scale of comparable numbers that accurately reflected the wide range of hardnesses found in steels.

The indenter employed in the Vickers test is a square-based pyramid whose opposite sides meet at the apex at an angle of 136°. The diamond is pressed into the surface of the material at loads ranging up to approximately 120 kilograms-force, and the size of the impression (usually no more than 0.5 mm) is measured with the aid of a calibrated microscope. The Vickers number (HV) is calculated using the following formula:

$$HV = 1.854(F/D^2),$$

with F being the applied load (measured in kilograms-force) and D² the area of the indentation (measured in square millimetres). The applied load is usually specified when HV is cited.

The Vickers test is reliable for measuring the hardness of metals, and also used on ceramic materials. The Vickers testing method [10] is similar to the Brinell test. Rather than using the Brinell's steel ball type indenter, and have to calculate the hemispherical area of impression, the Vickers machine uses a penetrator that is square in shape, but tipped on one corner so it has the appearance of a playing card "diamond". The Vickers indenter is a 136 degrees square-based diamond cone, the diamond material of the indenter has an advantage over other indenters because it does not deform over time and use. The impression left by the Vickers penetrator is a dark square on a light background. The Vickers impression is more easily "read" for area size than the circular impression of the Brinell method. Like the Brinell test, the Vickers number is determined by dividing the load by the surface area of the indentation ($H = P/A$). The load varies from 1 to 120 kilograms. To perform the Vickers test, the specimen is placed on an anvil that has a screw threaded base. The anvil is turned raising it by the screw threads until it is close to the point of the indenter. With start lever activated, the load is slowly applied to the indenter. The load is released and the anvil with the specimen is lowered. The operation of applying and removing the load is controlled automatically.

Several loadings give practically identical hardness numbers on uniform material, which is much better than the arbitrary changing of scale with the other hardness machines. A filar microscope is swung over the specimen to measure the square indentation to a tolerance of plus or minus 1/1000 of a millimeter. Measurements taken across the diagonals to determine the area, are averaged. The correct Vickers designation is the number followed "HV" (Hardness Vickers). The advantages of the Vickers hardness test are that extremely accurate readings can be taken, and just one type of indenter is used for all types of metals and surface treatments. Although thoroughly adaptable and very precise for testing the softest and hardest of materials, under varying loads, the Vickers machine is a floor standing unit that is rather

more expensive than the Brinell or Rockwell machines [11].

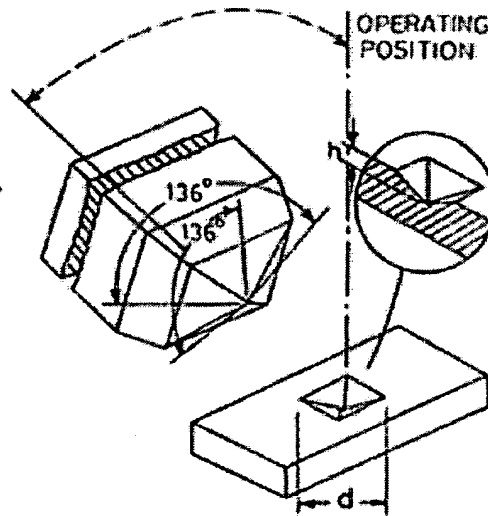


Figure 3

3.4. Knoop hardness

The relative microhardness of a material is determined by the Knoop indentation test. In this test, a pyramid-shaped diamond indenter with apical angles of 130° and $172^\circ 30'$ (called a Knoop indenter) is pressed against a material. Making a thombohedral impression with one diagonal seven times longer than the other. The hardness of the material is determined by the depth to which the Knoop indenter penetrates [12].

This test method was devised in 1939 by F. Knoop and colleagues at the National Bureau of Standards in the United States. By using lower indentation pressures than the Vickers hardness test, which had been designed for measuring metals, the Knoop test allowed the hardness testing of brittle materials such as glass and ceramics.

The diamond indenter employed in the Knoop test is in the shape of an elongated four-sided pyramid, with the angle between two of the opposite faces being approximately 170° and the angle between the other two being 130° . Pressed into the material under loads that are often less than one kilogram-force, the indenter leaves a four-sided impression about 0.01 to 0.1 mm in size. The length of the impression is approximately seven times the width, and the depth is $1/30$ the length. Given such dimensions, the area of the impression under load can be calculated after measuring only the length of the longest side with the aid of a calibrated microscope. The final Knoop hardness (HK) is derived from the following formula:

$$HK = 14.229(F/D^2),$$

with F being the applied load (measured in kilograms-force) and D^2 the area of the indentation (measured in square millimetres). Knoop hardness numbers are often cited in conjunction with specific load values.

ASTM D-1474 deals with standard test methods for indentation hardness of organic coatings. In this

test, Knoop hardness determinations are made at $23 \pm 2^\circ \text{C}$ and $50 \pm 5\%$ relative humidity. The specimens are equilibrated under these conditions for at least 24 hours. They are then rigidly attached to the movable stage so that the surface to be measured is normal to the direction of the indentation. The apparatus is preset to apply a 25 g load. The time the indenter is in contact with the specimen should be 18 ± 0.5 seconds. The length of the long diagonal of the impression is measured with the filar micrometer eyepiece. The procedure is repeated until at least five impressions have been made at widely spaced locations. The Knoop hardness number is then calculated by

$$KHN = \frac{0.0025}{l^2 C_p}$$

where 0.0025 is the load applied in kg to the indenter, l is the length of the long diagonal of the indentation in mm, and C_p is the indenter constant, equal to 7.028×10^{-2} .

ASTM D-785 is the standard test for determining the Rockwell hardness of plastics and electrical insulating materials. A minor load of 10 kg, which is built into the machine, is first applied without shock. Within 10 seconds after applying the minor load and immediately after set position is obtained, the major load is applied on the specimen. The major load is removed 15 seconds after its application. The Rockwell hardness is read off the scale on the machine. Care should be taken in choosing the proper scale, as Rockwell hardness values are reported as a letter, indicating the scale, and a number, indicating the reading [13].

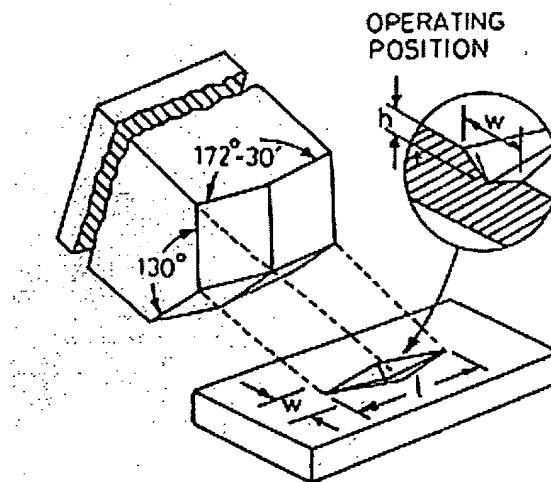


Figure 4

3.5. Shore

The shore scleroscope measures hardness in terms of the elasticity of the material. A diamond-tipped hammer in a graduated glass tube is allowed to fall from a known height on the specimen to be tested, and the hardness number depends on the height to which the hammer rebounds; the harder the material, the higher the rebound [14].

Shore hardness [15] is a measure of the resistance of material to indentation by 3 spring-loaded indenter. The higher the number, the greater the resistance.

The hardness testing of plastics is most commonly measured by the Shore (Durometer) test or Rockwell hardness test. Both methods measure the resistance of the plastic toward indentation. Both scales provide an empirical hardness value that doesn't correlate to other properties or fundamental

characteristics. Shore Hardness, using either the Shore A or Shore D scale, is the preferred method for rubbers/elastomers and is also commonly used for 'softer' plastics such as polyolefins, fluoropolymers, and vinyls. The Shore A scale is used for 'softer' rubbers while the Shore D scale is used for 'harder' ones. The shore A Hardness is the relative hardness of elastic materials such as rubber or soft plastics can be determined with an instrument called a Shore A durometer. If the indenter completely penetrates the sample, a reading of 0 is obtained, and if no penetration occurs, a reading of 100 results. The reading is dimensionless.

The Shore hardness is measured with an apparatus known as a Durometer and consequently is also known as 'Durometer hardness'. The hardness value is determined by the penetration of the Durometer indenter foot into the sample. Because of the resilience of rubbers and plastics, the hardness reading may change over time - so the indentation time is sometimes reported along with the hardness number. The ASTM test number is ASTM D2240 while the analogous ISO test method is ISO 868.

The results obtained from this test are a useful measure of relative resistance to indentation of various grades of polymers. However, the Shore Durometer hardness test does not serve well as a predictor of other properties such as strength or resistance to scratches, abrasion, or wear, and should not be used alone for product design specifications.

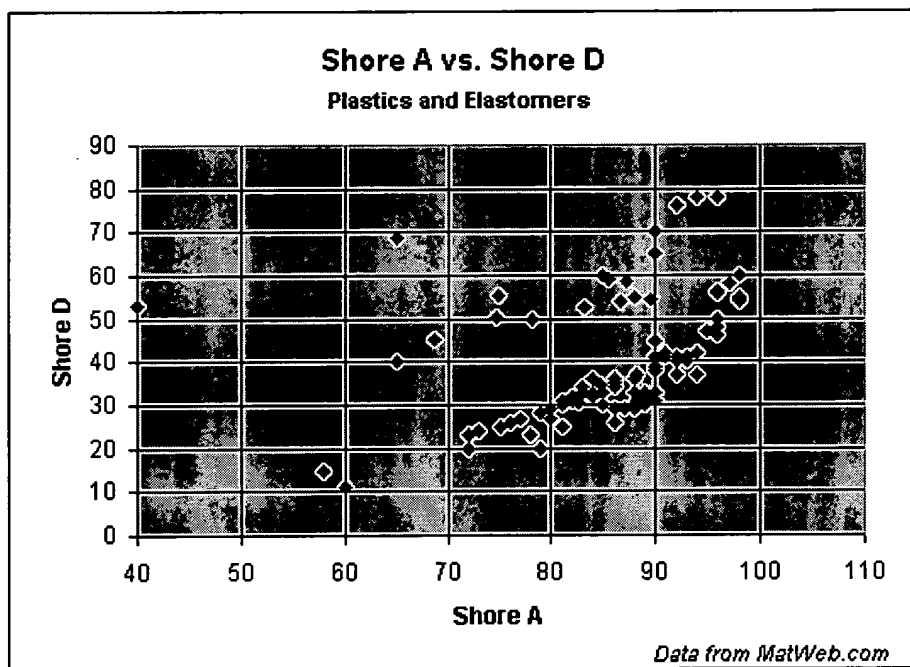


Figure 5. Shore A vs. Shore D

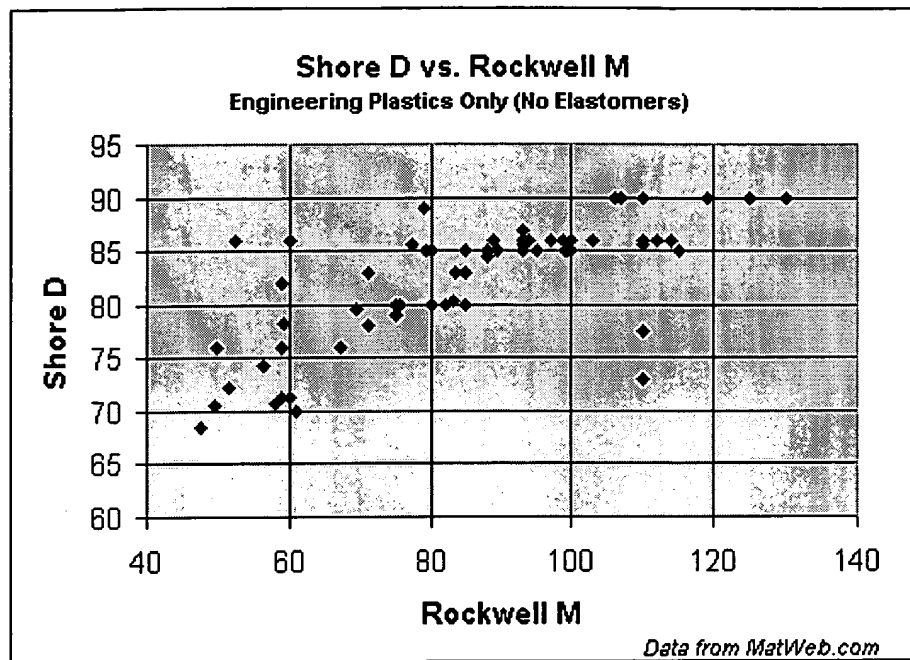


Figure 6. Shore D vs. Rockwell M [16]

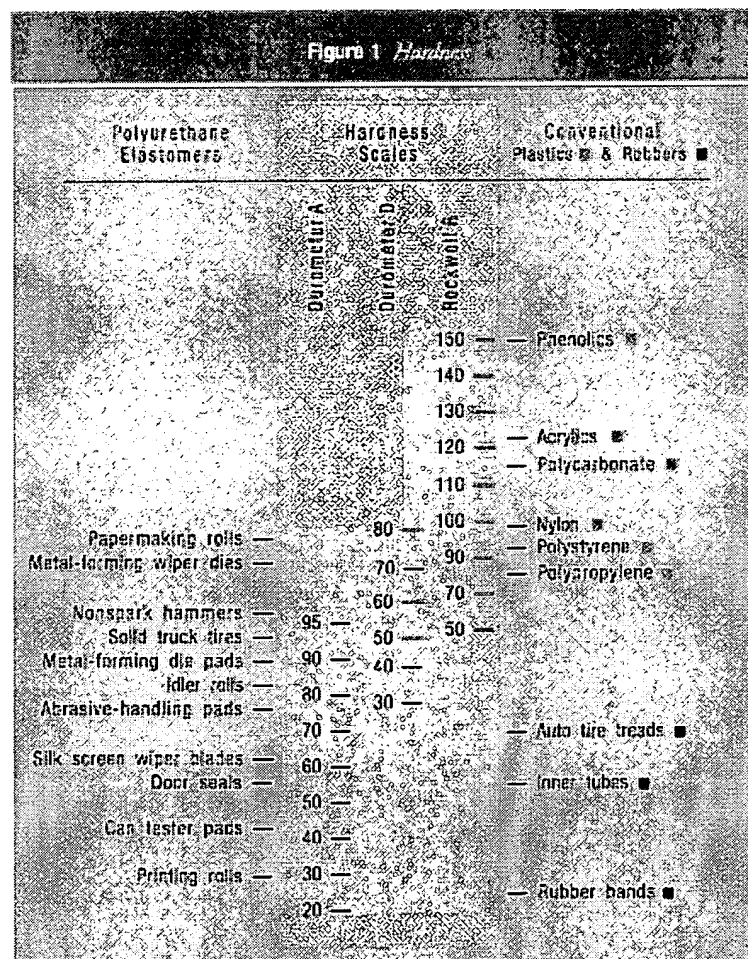


Figure 7. Hardness comparison scale of some materials [17]

Others

3.6.1. Mohs Hardness:

Mohs hardness is defined by how well a substance will resist scratching by another substance [18]. It is rough measure of the resistance of a smooth surface to scratching or abrasion, expressed in terms of a scale devised (1812) by the German mineralogist Friedrich Mohs. The Mohs hardness [19] of a mineral is determined by observing whether its surface is scratched by a substance of known or defined hardness.

To give numerical values to this physical property, minerals are ranked along the Mohs scale, which is composed of 10 minerals that have been given arbitrary hardness values. The minerals contained in the scale are shown in the Table; also shown are other materials that approximate the hardness of some of the minerals. As is indicated by the ranking in the scale, if a mineral is scratched by orthoclase but not by apatite, its Mohs hardness is between 5 and 6. In the determination procedure it is necessary to be certain that a scratch is actually made and not just a "chalk" mark that will rub off. If the species being tested is fine-grained, friable, or pulverulent, the test may only loosen grains without testing individual mineral surfaces; thus certain textures or aggregate forms may hinder or prevent a true hardness determination. For this reason the Mohs test, while greatly facilitating the identification of minerals in the field, is not suitable for accurately gauging the hardness of industrial materials such as steel or ceramics. (For these materials a more precise measure is to be found in the Vickers hardness or Knoop hardness;) Another disadvantage of the Mohs scale is that it is not linear; that is, each increment of one in the scale does not indicate a proportional increase in hardness. For instance, the progression from calcite to fluorite (from 3 to 4 on the Mohs scale) reflects an increase in hardness of approximately 25 percent; the progression from corundum to diamond, on the other hand (9 to 10 on the Mohs scale), reflects a hardness increase of more than 300 percent.

3.6.2. Barcol Hardness

Barcol hardness is a method that a hardness value obtained by measuring the resistance to penetration of a sharp steel point under a spring load. The instrument, called the Barcol impressor, gives a direct reading on a 0 to 100 scale. The hardness value is often used as a measure of the degree of cure of a plastic.

ASTM D2583 Barcol Hardness test method is used to determine the hardness of both reinforced and non-reinforced rigid plastics. The specimen is placed under the indenter of the Barcol hardness tester and a uniform pressure is applied to the specimen until the dial indication reaches a maximum. The depth of the penetration is converted into absolute Barcol numbers.

Barcol hardness values are also used to determine degree of cure of resin. Resin is considered cured when it has a hardness value greater than or equal to 90% of the surface hardness value.

4. HARDNESS OF ELECTRONIC PACKAGING MATERIALS:

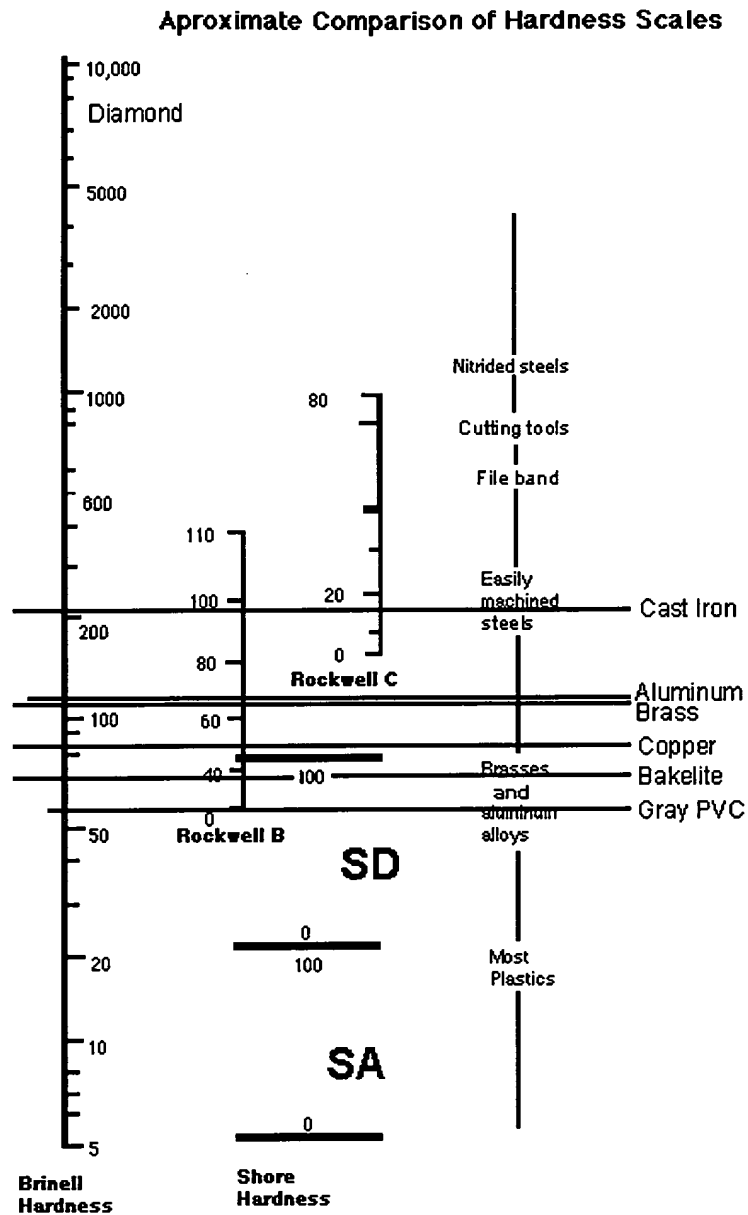
Material	Rockwell	Brinell	Knoop	Vickers	Shore	Mohs
Copper Film			153.3 KP			
Kovar (53Fe + 29 Ni + 17 Co)	68.0 RW (B)	120				
NEMA FR-4 Glass Fiber/Epoxy Composite	110.0 RW					
Aluminum Film				0.587 VR		

Diamond Film			65 GPa	72.8 VR (29 - 118 Gpa)		
Tungsten Film				19.885 VR		
Alumina, Al(2)O(3)				19.81 VR		9
Aluminum Nitride				12.20 VR		
Silicon Nitride				17.46 VR		
Die attach	Silicone				20-90A ^a	

Table. Hardness values of common packaging materials

KP: Knoop Hardness; RW : Rockwell Hardness; VR : Vickers Hardness, b: glass or mineral filled, c: casting/liquid resins

5. COMPARISION OF HARDNESS MEASUREMENTS



Mark Doggett IT 283

Figure 8. Comparison of hardness scales

TEST	TEST METHOD	TEST FORCE RANGE	INDENTER TYPES	ASTM TEST METHOD	MEASURE METHOD
Rockwell	Regular	60, 100, 150 kgs	Conical Diamond & Small Ball	E 18	Depth
	Superficial	15, 30, 45 kgs	Conical Diamond & Small Ball	E 18	Depth
	Light Load	3, 5, 7 kgs	Truncated Cone Diamond	N/A	Depth
	Micro	500, 100 grams	Small Truncated Cone Diamond	N/A	Depth
	Macro	500 to 3000 kgs	5, 10 mm Ball	E 103	Depth
Micro-Hardness	Vickers	5 to 2000 grams	136° Pyramid Diamond	E 384	Area
	Knoop	5 to 2000 grams	1300 x 1720° Diamond	E 384	Area
	Rockwell Type	500, 3000 grams	Truncated Cone Diamond	N/A	Depth
	Dynamic	01 to 200 grams	Triangular Diamond	N/A	Depth
Brinell	Optical	500 to 3000 kgs	5mm, 10 mm Ball	E 10	Area
	Depth	500 to 3000 kgs	5mm, 10 mm Ball	E 103	Depth
Shore	Regular	622 (A), 4550 (D) grams	35° Cone (A) 30° Cone (D)	D 2240	Depth
	Micro	257 (A), 1135 (D) grams	35° Cone (A) 30° Cone (D)	N/A	Depth
IRHD	Regular	597 grams	2.5 mm Ball	D 1415	Depth
	Micro	15.7 grams	395 mm Ball	D 1415	Depth

Figure 9. The summary table for different hardness testing methods [26]

6. HARDNESS MEASUREMENT EQUIPMENTS



Figure 10. A portable and fast hardness gauge, for testing Aluminum, mild steel, brass and copper with thickness range of 0.025 to 1/4 inch. It is used for identifying heat-treated from non-heat-treated parts, provides correlation between a bench mounted hardness tester and the production line, for segregating materials in stock, for differentiating between soft or work-hardened material, for identifying parts made from improper or substandard alloys, checking for proper heat-treatment response, useful in conjunction with stationary laboratory hardness testers.

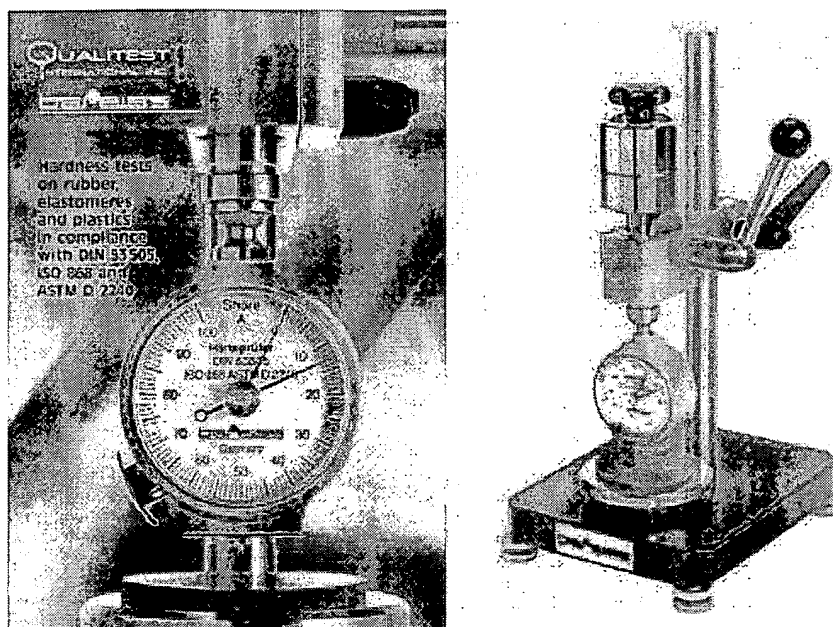


Figure 11-12. For hardness determination of plastics and elastomers according to A, D, B, C, DO, O and OO scales. Used in the hardness determination on all natural and synthetic rubber products, acrylic glass, acetates, casting resin, polyester, thermoplastics, PVC, neoprenes and etc

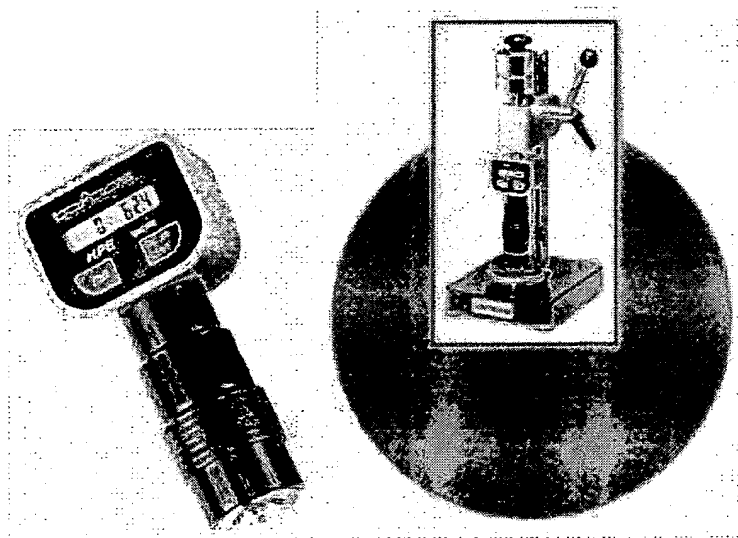


Figure 13-14. The digital durometer HPE, serves for the hardness determination of rubber, elastomers, and plastics within the durometer ranges A, D, B, O, OO, C, and DO.

Alloy Steel Threaded Rods

Pressure Lever

Bourdon-Type Pressure Gauge

Stainless Steel Test Head

Gear Train with Hand Crank

Standard 10mm Brinell Ball

Handles

Throat

Flat, Dome and Vee Anvils

Wire Bracket

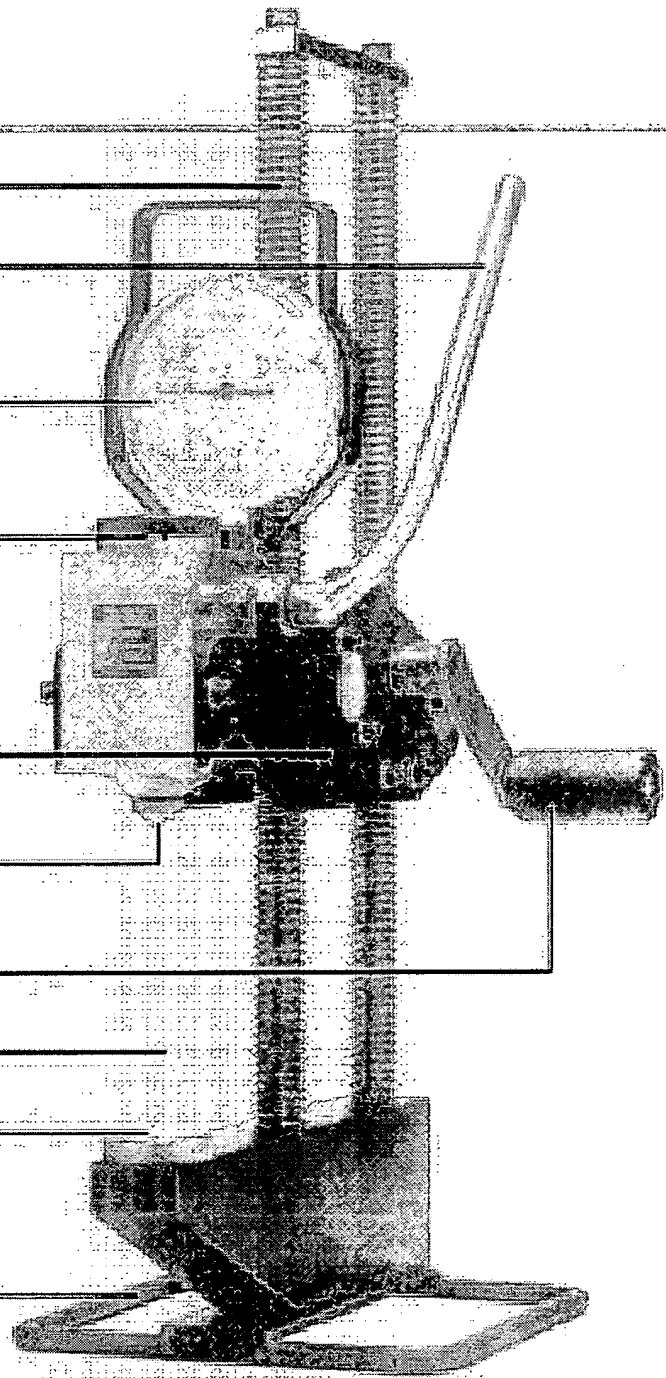


Figure 15. Brinell Hardness Tester

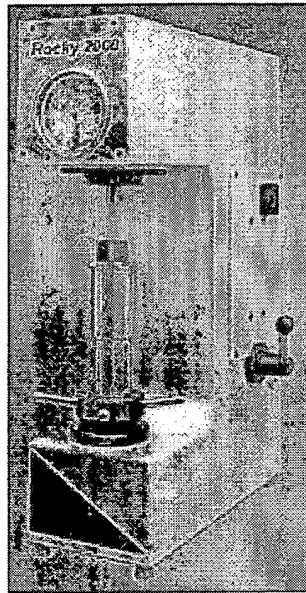


Figure 16. Rockwell test consists of checking the resistance of a sample, to be penetrated by a hard metal ball or by a conical shaped diamond, under the pressure of a load. This test proceeds in two steps. At first the penetration start point (zero) under a minor or preliminary load is determined, and the second step happens under a major load. The latent deformation measured after releasing the major load, is a direct measure of the Rockwell hardness, which is given on the scale of the dial gauge.

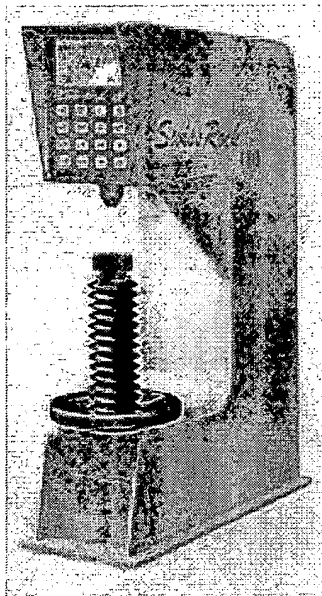


Figure 17. With digital display for Rockwell A, B, C and superficial hardness testing.

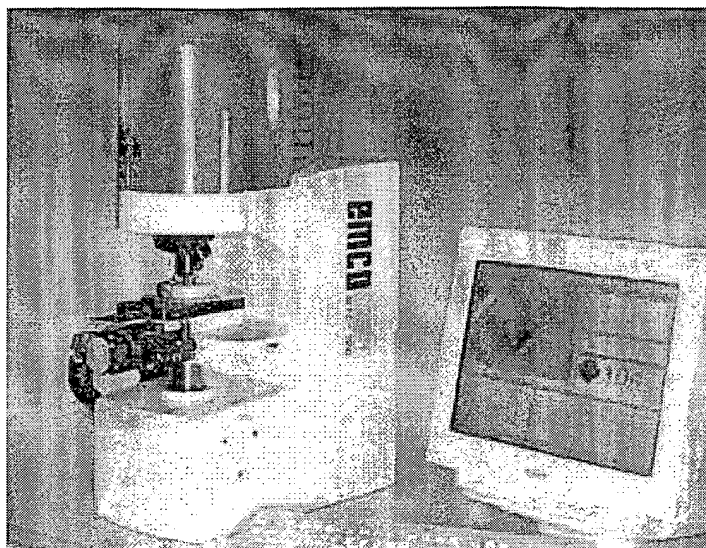


Figure 18. Digital Low Load Tester for Vickers, Brinell, and Knoop Load range HV 0.1 - HV 30

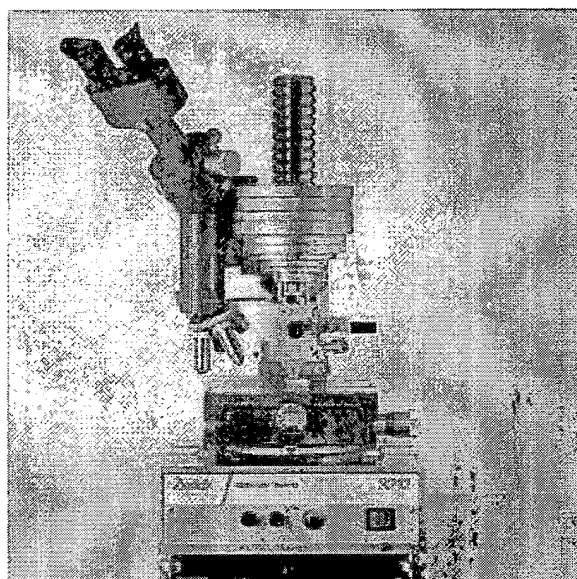


Figure 19. Analog hardness tester for Vickers, Knoop, Brinell and Scoring With Micro and Macro load attachments

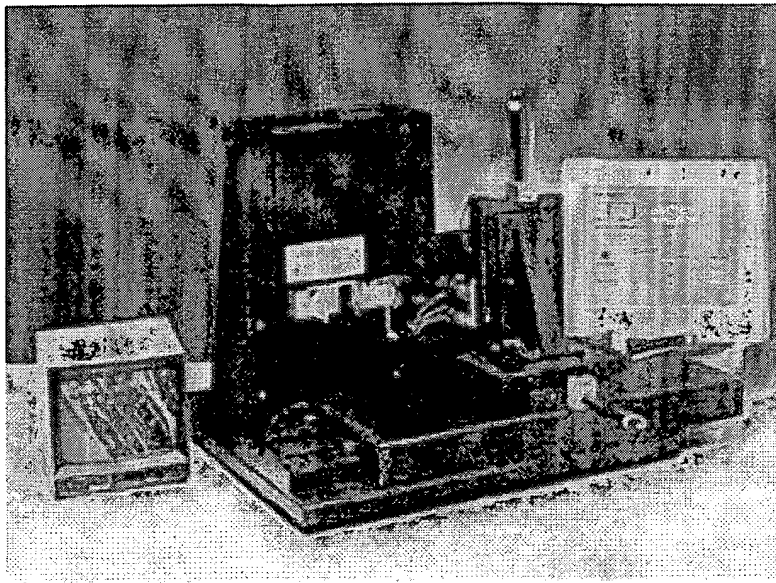


Figure 20. The Nano Tester supports indentation, scratching and impact.

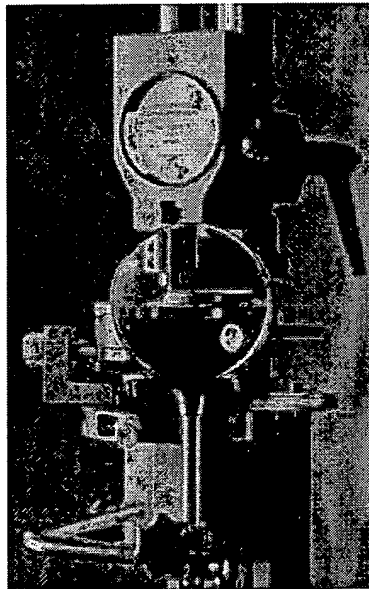


Figure 21. Equipment for hardness determination of Plastics, Elastomers, O-Rings, Seals, Gaskets, Rubber Rollers.

Rockwell C Scale	Brinell Hardness	Vickers Hardness	Tensile Strength (approx.)		Rockwell C Scale	Brinell Hardness	Vickers Hardness	Tensile Strength (approx.)	
Brale Penetrator	10mm Tungsten Carbide Ball	Pyramidal Diamond			Brale Penetrator	10mm Tungsten Carbide Ball	Pyramidal Diamond		
150kgf	3,000kgf	10kgf	ks	kg/mm ²	150kgf	3,000kgf	10kgf	ks	kg/mm ²
67	—	900	—	—	43	400	423	201	141
66	—	865	—	—	42	390	412	196	138
65	739	832	—	—	41	381	402	191	134
64	722	800	—	—	40	371	392	186	131
63	705	772	—	—	39	362	382	181	127
62	688	746	—	—	38	353	372	176	124
61	670	720	—	—	37	344	363	172	121
60	654	697	—	—	36	336	354	167	118
59	634	674	329	232	35	327	345	163	114
58	615	653	319	224	34	319	336	159	112
57	595	633	307	216	33	311	327	154	109
56	577	613	297	209	32	301	318	149	105
55	560	595	288	202	31	294	310	146	102
54	543	577	279	196	30	286	302	142	99
53	525	560	269	189	29	279	294	138	97
52	512	544	262	184	28	271	286	134	94
51	496	528	253	178	27	264	279	130	92
50	481	513	245	172	26	258	272	127	89
49	469	498	238	167	25	253	266	125	88
48	455	484	231	162	24	247	260	122	85
47	443	471	224	158	23	243	254	120	84
46	432	458	218	153	22	237	248	116	82
45	421	446	212	149	21	231	243	113	80
44	409	434	206	145	20	226	238	111	78

For the source of Rockwell, Brinell and Vickers Hardness data see endnote 4.

Figure 22 Hardness units conversion table [27]

7. RELATION OF HARDNESS TO OTHER MATERIAL PROPERTIES

Hardness covers several properties: resistance to deformation, resistance to friction and abrasion.

The well known correlation links hardness with tensile strength, while resistance to deformation is dependent on modulus of elasticity. The frictional resistance may be divided in two equally important parts: the chemical affinity of materials in contact, and the hardness itself.

So it is easy to understand that surface treatments modify frictional coefficients and behaviour of the parts in contact. The abrasion resistance is partially related to hardness (between 2 metallic parts in frictional contact, the less hard one will be the more rapidly worn), but experiments carried out at Centre de Recherches PECHINEY in Voreppe (CRV), with TABER test show that the correlation resistance against wear/ hardness presents some inversions [28]

A correlation may be established between hardness and some other material property such as tensile strength. Then the other property (such as strength) may be estimated based on hardness test results, which are much simpler to obtain. This correlation depends upon specific test data and cannot be extrapolated to include other materials not tested.

The yield strength in tension is about 1/3 of the hardness [29]. To find the ball park figure for the yield strength convert the hardness number to MPa (or psi) and divide by 3. For example take the Vickers number, which has the dimension kg/mm², and multiply by 10 to (approximately) convert it to /mm² (=MPa) then divide by three.

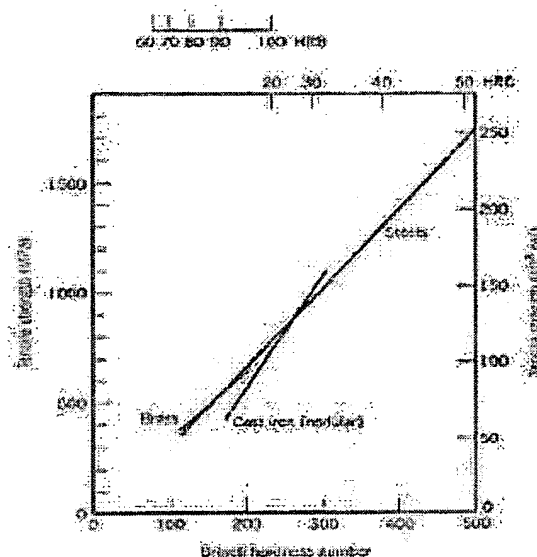
For example: HV 300 corresponds to a Sigma-y of approximately 1000 MPa. An approximate relationship between the hardness and the tensile strength (of steel) is,

$$TS \text{ (MPa)} = \begin{cases} 3.55 \cdot HB & (HB \leq 175) \\ 3.38 \cdot HB & (HB > 175) \end{cases}$$

$$TS \text{ (psi)} = \begin{cases} 515 \cdot HB & (HB \leq 175) \\ 490 \cdot HB & (HB > 175) \end{cases}$$

Where HB is the Brinnell Hardness of the material, as measured with a standard indenter and a 3000 kgf load.

Hardness & Tensile Strength



$$\sigma_{TS} = 500 \times HB$$

Figure 23. Harfdness & Tensile Strength [30]

Wear is generally affected by several factors, among them materials selection, friction, surface load, sliding distance, surface hardness, surface finish, and lubrication. Controlling these factors can contribute to a successful application by helping to prevent wear and premature product failure. Wear can be defined as both material loss and deformation at contact surfaces. Wear results in particle generation and surface degradation

Properties are high wear resistance; high strength, hardness and fracture toughness; low porosity; high creep and corrosion resistance; The hardness of a metal limits the ease with which it can be machined, since toughness decreases as hardness increases. Toughness is a combination of high strength and medium ductility. It is the ability of a material or metal to resist fracture, plus the ability to resist failure after the damage has begun. A tough metal, such as cold chisel, is one that can withstand considerable stress, slowly or suddenly applied, and which will deform before failure. Toughness is the ability of a material to resist the start of permanent distortion plus the ability to resist shock or absorb energy [31].

8. REFERENCES

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